Absolute calibration of Single Photon Detectors using Parametric Down Conversion

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Outline :

1.What is Parametric Down Conversion (PDC)?

1. 2. Using PDC to absolute calibrate SPD (Klyshko)-results obtained in the literature.

2. 3. Practical issues: losses, accidentals, backgrounds, uncertainty budget

3. 4. Doing this at SiDet: possible lay-outs, current status, what we need for the future, long range plans.

Motivation

SiPM's as the photon detector for a L Ar TPC (more in S. Mufson's talk on Monday, 6/18)

SiPM pros:

Hi gain, low power consumption, no HV system, work in magnetic fields, single photon sensitivity, very good time resolution, well suited for cryogenic environments.

SiPM cons:

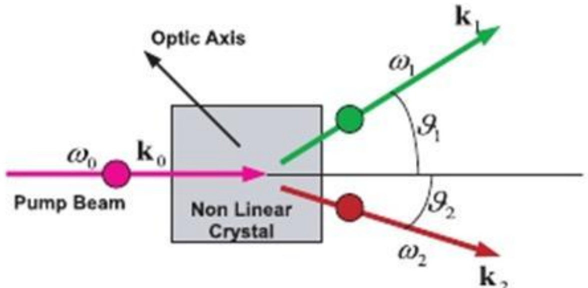
Dark count rate, small size, cost/mm*2, low PDE in the blue and UV region

but this is changing fast (more at the end)

These devices need to be better understood by the users community like what happened with PMT: positive interaction between users and manufacturers led to better knowledge of them

What is Parametric Down Conversion (PDC)?

- Frequency conversion in a non-linear medium , whereby an incident photon (pump) is converted into two smaller frequency photons (signal and idler) obeying conservation of energy and momentum (non-centro symmetric crystals).
- Exploits bi-refrigency of the non-linear medium (extraordinary and ordinary rays have different refraction indices) .
- Twin photons are correlated in number and frequency
- Type I PDC: e → o + o e-ray pol //o-axis plane ; o-ray pol. orthogonal
- Spontaneous PDC

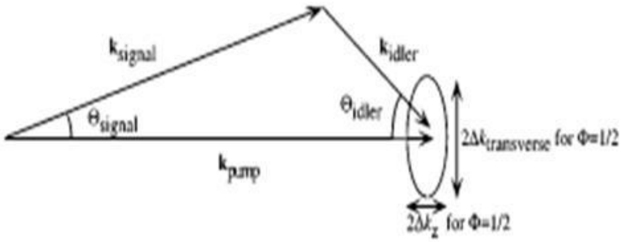


$$\mathbf{k}_0 = \mathbf{k}_1 + \mathbf{k}_2$$
$$\omega_0 = \omega_1 + \omega_2$$

Examples of SPDC

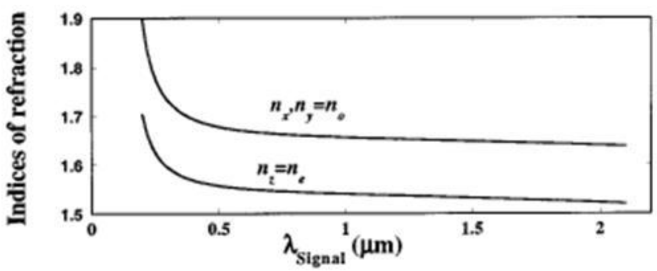
- Typical crystals: beta barium borate (BBO); KDP, LiIO3 – uniaxial crystals.
- BBO a commonly used , negative crystal (extraordinary ray is faster than the ordinary ray)
- Phase matching conditions (stick to type I PDC):

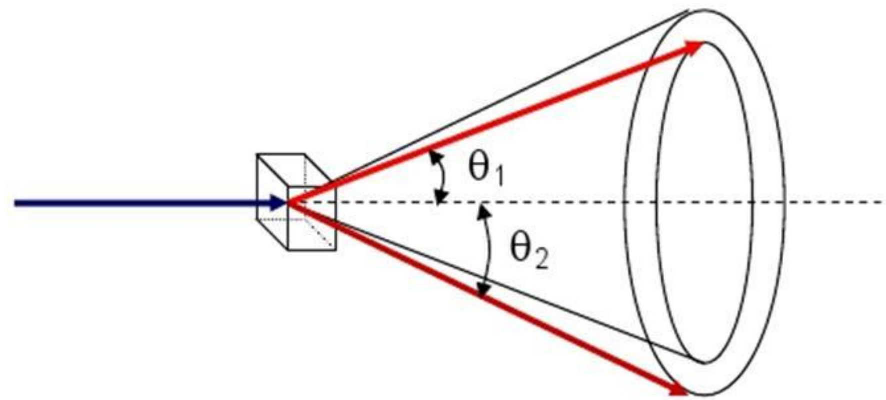
more later on.



SPDC examples:

- First thing is choosing the crystal given wavelength of pump and desired range of wavelengths for the down converted pair:





- BBO crystal

- Energy conservation and phase matching eqs. provide a range of angles and wavelengths for the twin photons.

Degenerate configuration: signal and idler same frequency: : $\omega 1 = \omega 2 = \omega p/2$

For BBO at pump $\lambda = 405$ nm, signal and idler are at $\lambda = 810$nm and theta = 3 degrees

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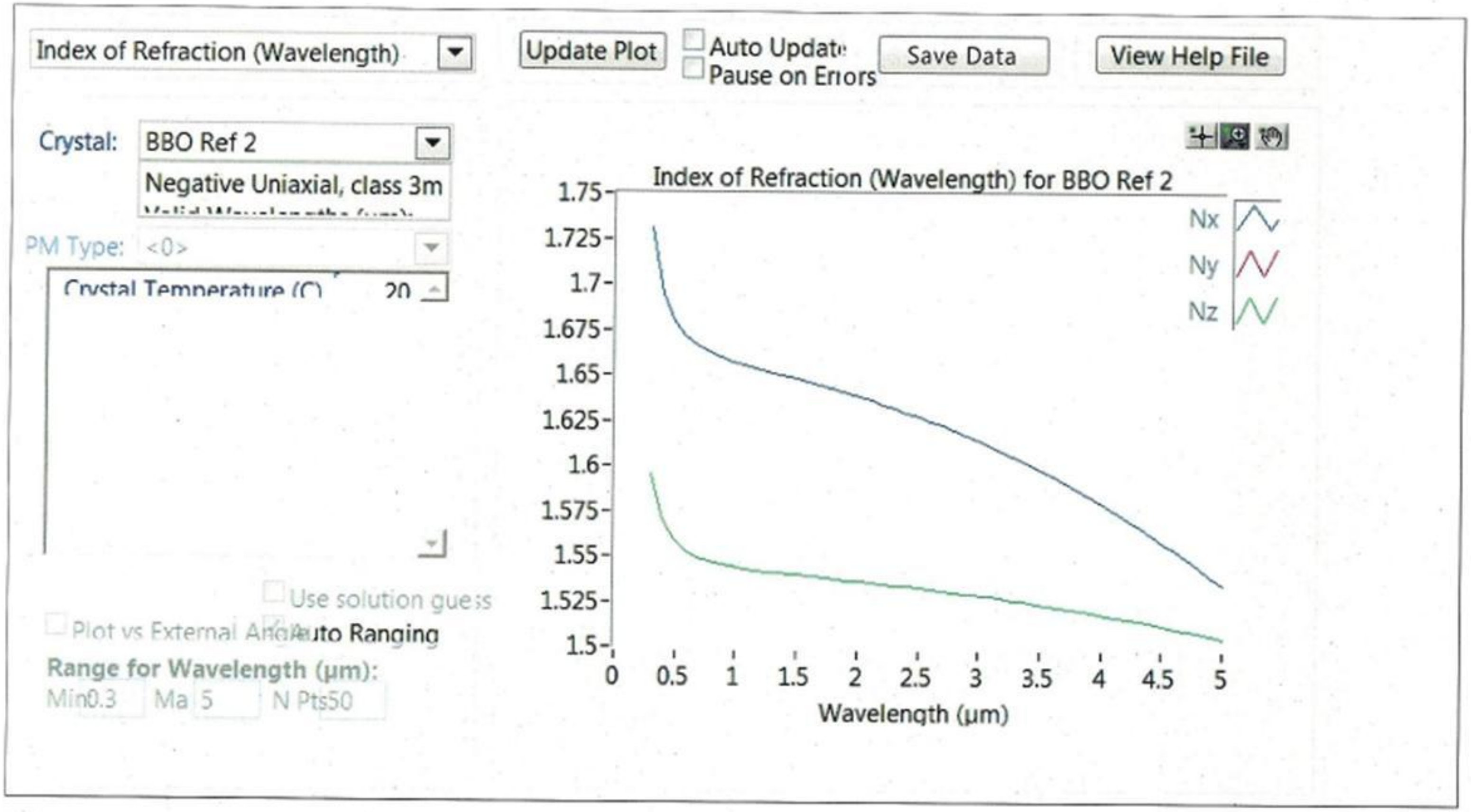
Choosing wavelengths and angles



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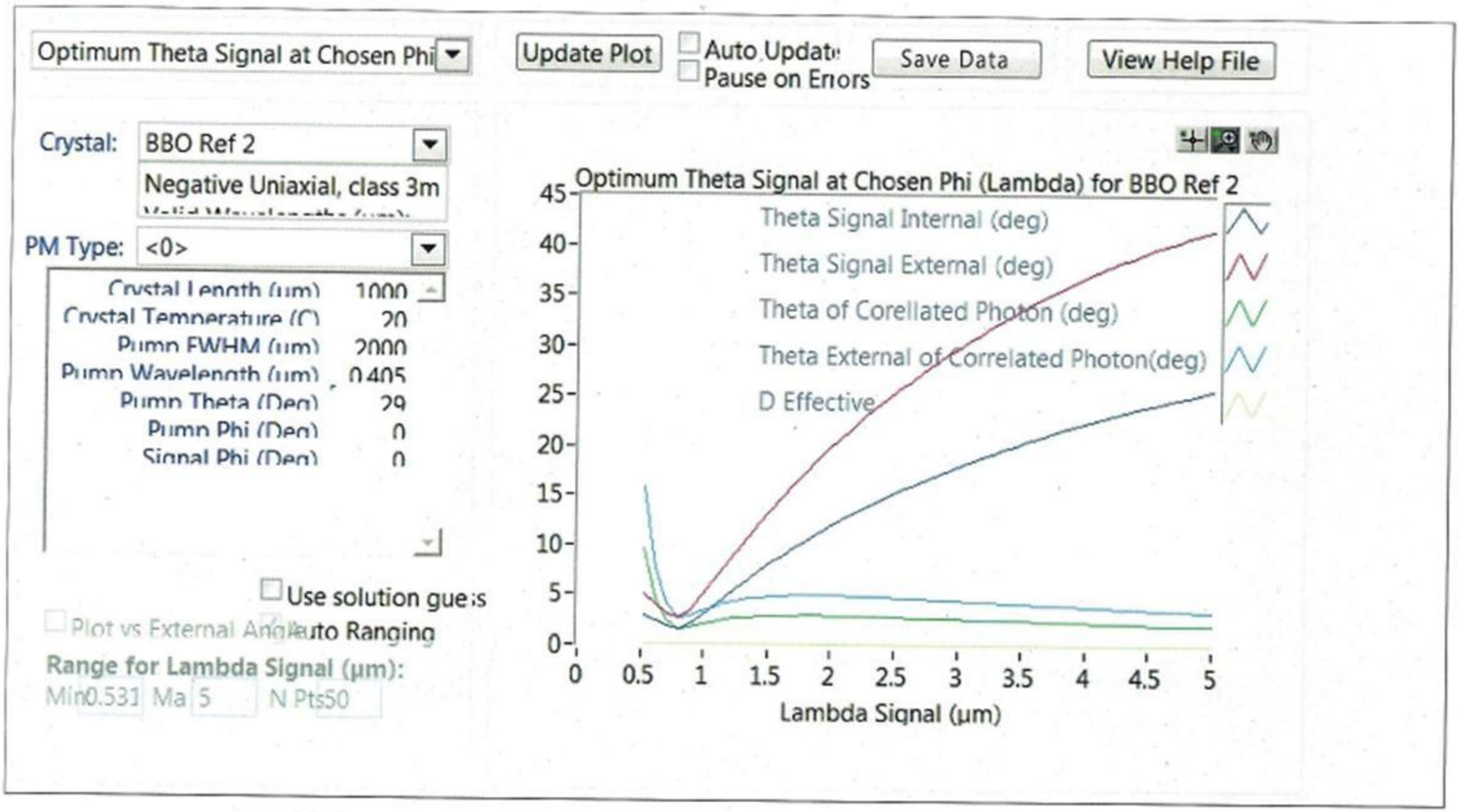
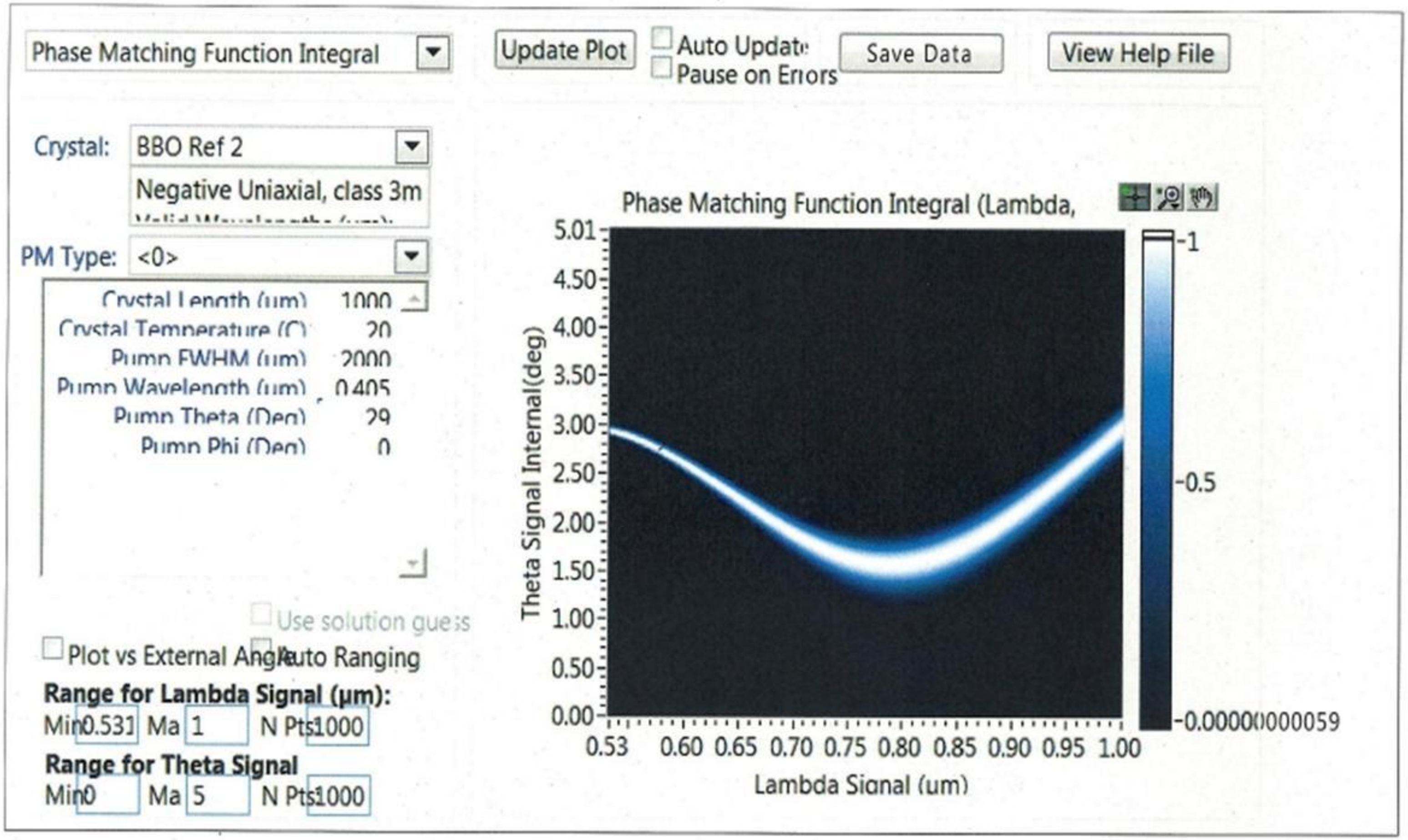
wavelengths and angles cont.

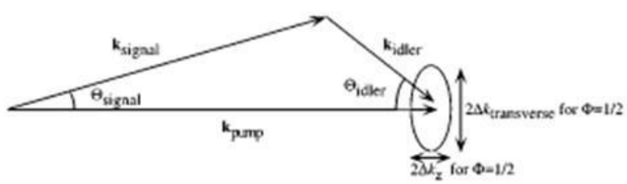


Range of λ and θ



Quasi-phase matching ref. Boeuf, Migdall et al. (NIST) Opt. Eng. 39, 1016 (2000)

Easier to have phase matching in a finite, small crystal than in a long one: uncertainty principle: $\Delta k \Delta l$=const



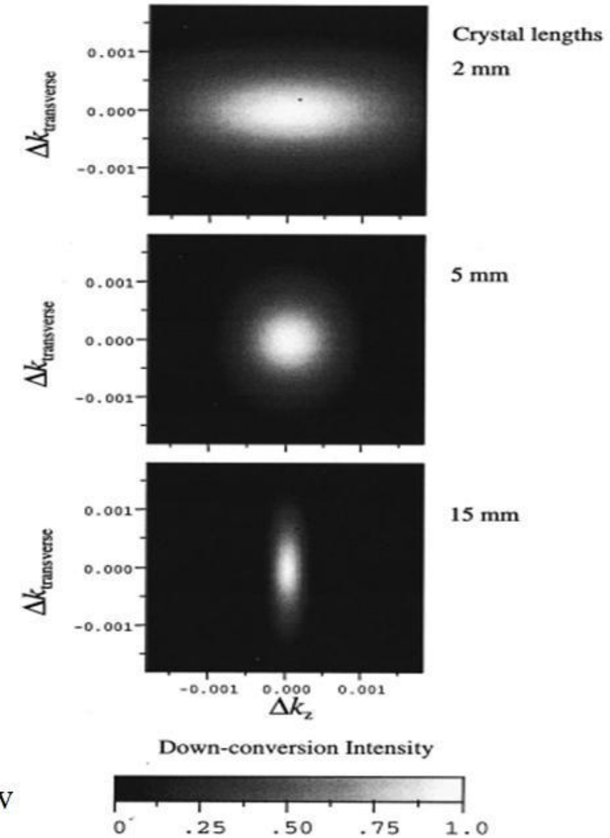


Fig. 7 Phase-matching function for KDP crystals of three different lengths and constant pump beam width of 2 mm (FWHM).

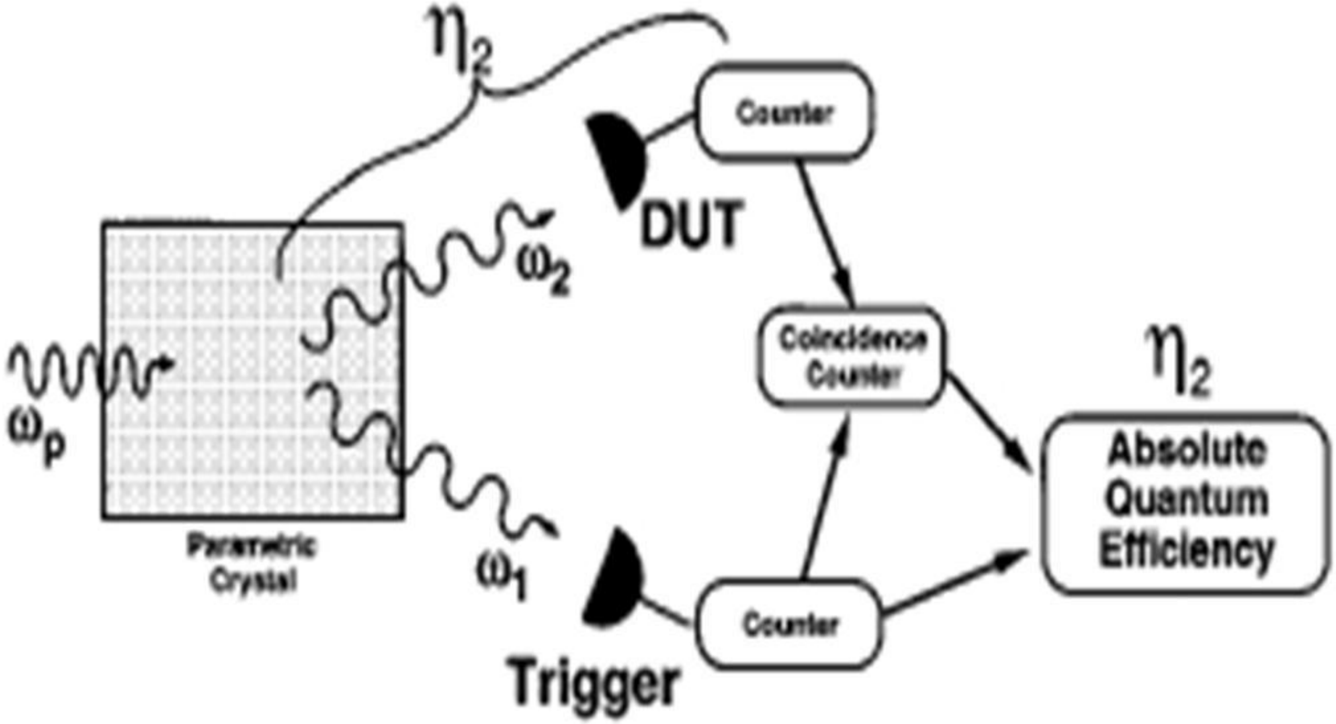
Klyshko's method (ref. Sov. J. Quantum Electron. **10,** 1112 (1980))

Exploits the correlation in number of the bi-photon field: if one photon is detected (idler) one knows for sure that there is another photon (with a well defined frequency) in the other arm (signal).

Use idler to trigger a detector and detect signal with the Device Under Test (DUT)

Register single counts in both arms and count the coincidences between trigger and DUT.

Klyshko's method cont.



Klyshko meth. Cont.

- $N_1 = \eta_1 N$ (N # of pairs)
- $N_2 = \eta_2 N$
- $N_C = \eta_1 \eta_2 N$

$$\eta_2 = N_C / N_1$$

NB: η_2 includes DUT as well as optical path inefficiency(losses).

Practical issues

- 1. Accidentals
- 2. Background
- 3.Minimizing losses on DUT path
- 4. Selecting λ and angle of photon in the trigger

branch. (the fewer the optical elements on the DUT branch the better).

Practical issues cont.

- Taking account of accidentals and background:

$$\eta_2 = \{ N_C - N_a \} / \{ N_1 - N_B \}$$

Both the # of accidentals and the background can be measured.

Select the trigger photon in frequency and angle with filters and irises, by correlation signal photon is selected

How many twin photons do we expect?

- It is a number that can be measured, several groups have measured that the down conversion efficiency is of the order of 10^{-6} to 10^{-8} .
- # of twin photons is proportional to the length of the crystal and the power of the pump beam.
- A frequently quoted number for a fixed geometry

(azimuthal angle fixed is 1000pairs/mW/s

See Ling et al. Phys. Rev A **77,** 04384 (2008)

Several groups have used and are still using this method

- Pioneer papers:
- J. G. Rarity et al., Appl.Opt. **26,** 4616 (1987)
- P.G. Kwiat et al. Appl. Opt. **33,** 1844 (1994)
- ---
- Groups in Italy (Brida and coworkers), in France (INM) and in the US (Migdall and co-workers at NIST, Sergienko at BU)
- The method has become a standard in metrology with the above groups claiming accuracies of the order of 1% in the determination of PDE of photon detectors. (see refs at the end)

Efforts at SiDet

People involved:

Adam Para, Paul Rubinov, Donna Kubic and Carlos Escobar.

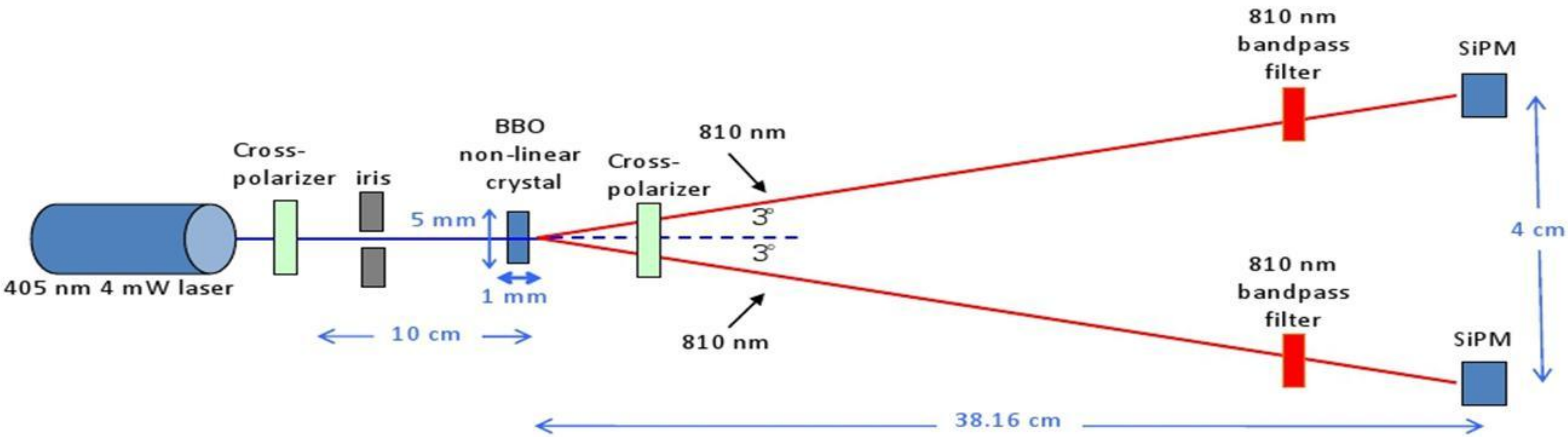
We set up a dark room with an optical table and will start making the first measurements with two lasers

One at 405nm and another at 375nm

(both diode lasers). We have two BBO crystals cut for type I. 3 degrees i& s

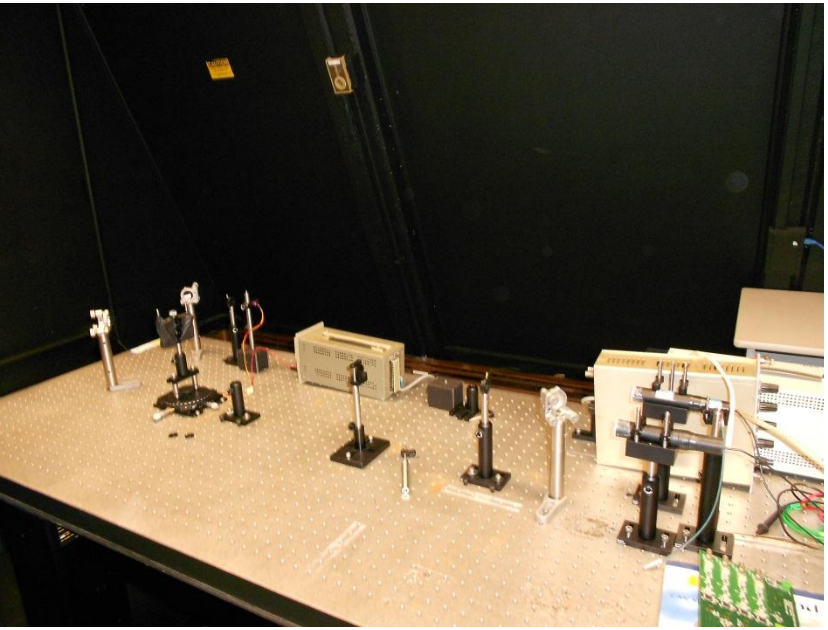
Possible lay-out

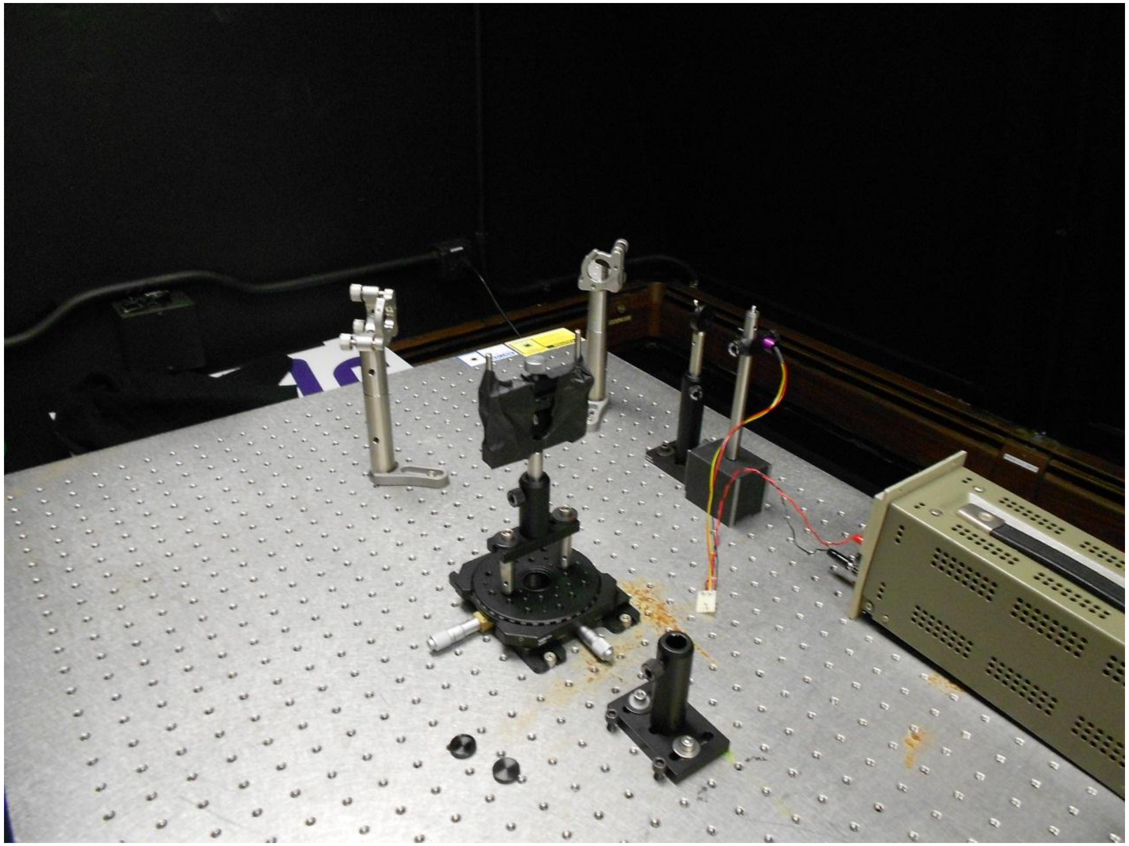
Non-collinear SPDC
405 nm,



angle		SiPM separation	distance of SiPM from BBO

Current set-up





Next:

Start characterizing several devices at the widest possible range of parameters; install cooling facilities; integrate this work within the work to be done with the 5 Ton TPC.

Very good time to do this as

SiPM's are improving very quickly, in 2-4 yrs expect:

PDE ≈ 50% -60% at 350-400 nm

high sensitivity to VUV light (20% - 40%)

Dark count rates below 50kHz/mm*2 at room temperature

timing for single photon < 50 ps (FWHM)

active area > 100mm*2

production costs < 1US$/mm*2

(from Musienko's talk at the CERN SiPM industry-academia matching event on Silicon Photomultipliers , Feb. 2011)

References

D. N. Klyshko, Sov. J. Quantum Electr. **10,** 1112(1980)

J. G. Rarity et al., Appl. Opt. **26,** 4616 (1987)

P. G. Kwiat et al. , Appl. Opt. **33,** 1844 (1994)

S. V. Polyakov and A. Migdall, Opt. Expr. **15**, 1390(2007)

G. Brida et al., Journal of Mod. Opt. **56**, 401(2009)

I. N. Agafonov et al. Opts. Lett. 36, 1329 (2011)

NIST software for phase-matching in PDC:

N. Bouef et al. Opt. Eng. **39**, 1016 (2000)

Backup slides

Klyshko's proposal
(from a commercial kit qutools: www.qutools.com-thanks to Adam Para)

qutools

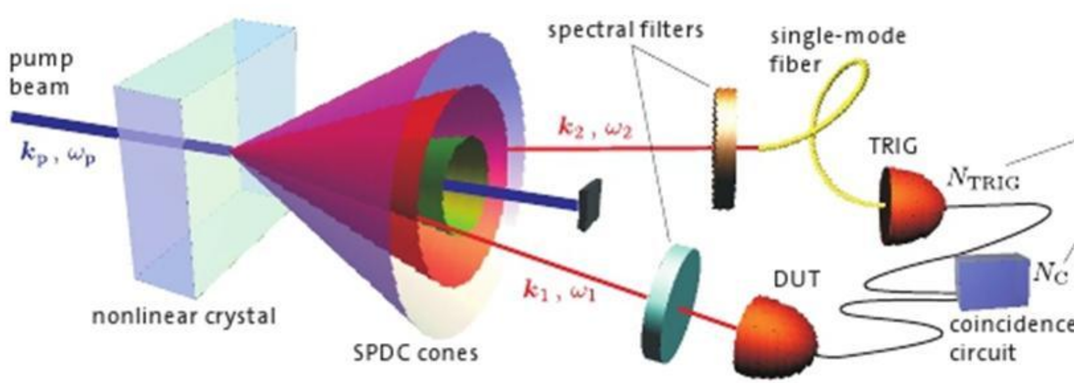


FIGURE 1. Basic optical arrangement for correlated-photon based efficiency calibration of photon-counting detectors.

arbitrary time unit, then the mean photon numbers N_{TRIG} and N_{DUT} registered by the two detectors and the number of detections N_{C} registered in coincidence are given by:

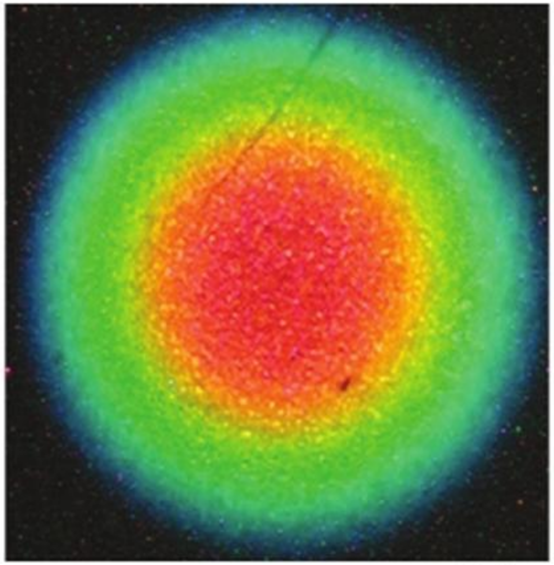
$$\begin{aligned} N_{\mathrm{TRIG}} &= \eta_{\mathrm{TRIG}} N, \\ N_{\mathrm{DUT}} &= \eta_{\mathrm{DUT}} N, \\ N_{\mathrm{C}} &= \eta_{\mathrm{TRIG}} \eta_{\mathrm{DUT}} N, \end{aligned}$$

where η_{TRIG} and η_{DUT} are the efficiencies of the detectors. As a result, the absolute value of η_{DUT} is simply detemined by:

$$\eta_{\mathrm{DUT}} = \frac{N_{\mathrm{C}}}{N_{\mathrm{TRIG}}}.$$

System design considerations

To minimize the calibration uncertainties, ideally all the photons correlated to those recorded by the trigger detector should reach the DUT detector. To this end, one adopts an unbalanced setup geometry, in which all the spectral and spatial filtering is concentrated into the trigger channel (see fig. 1). Practically, this is realized by inserting a narrow-band spectral filter and the single-mode fiber into the trigger channel, whereas only a pump-blocking filter (with a high transmission over the entire spectral band correlated to that defined by the narrowband filter) and a large collection aperture (letting pass all the correlated photons through, while restricting the number of uncorrelated photons) is used in the DUT channel.



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